SATELLITE SCIENCE AND TECHNOLOGY

By J. R. Pierce

Bell Telephone Laboratories, Murray Hill, New Jersey

The Halley Lecture for 1963, delivered at Oxford on May 15

MR. VICE-CHANCELLOR, LADIES AND GENTLEMEN,—

I am neither an historian nor an astronomer, and it would be presumptuous of me to comment at any length on either the life and work of Edmund Halley, or on the illustrious men who have delivered the Halley Lecture. I cannot help observing, however, the range of interests encompassed in Halley's work, which embraced geomagnetism as well as astronomy, the diligence with which he pursued it, and his bringing, through the publication of Newton's *Principia*, something beyond his own powers to the world of science.

The matters of which I shall speak in connection with satellite science and technology have an even wider range than Halley's work, because science is broader than it was in Halley's day. And, what I shall bring you today is not chiefly my own work, but rather the work of others.

Lest the title of my talk be misleading, I propose to talk almost exclusively about only one sort of satellite among the many that have been launched, that is, satellites intended to explore the possibilities of trans-oceanic communication. And, I shall further restrict myself almost exclusively to two experimental communication satellites, namely, Echo I and Telstar I.

Yet, in dealing with these seemingly specialized satellites, I shall have something to say about the Earth's atmosphere, its temperature and density a thousand miles above the Earth's surface, about the particles trapped in the Earth's magnetic field, about celestial mechanics, about an applied use of radio astronomy, and about the synchronization of clocks of the Royal Greenwich Observatory at Herstmonceux and the United States Naval Observatory at Washington, D.C. I shall also discuss some findings in the field of experimental psychology, and I shall touch on a remarkable political effect of the Echo and Telstar experiments.

Now all of this is only a small sample of the multitudinous scientific, technological and social problems which arose in connection with these communication satellites. Yet I believe that this small sample will show that if science and technology are only a part of the world of thought, they are a remarkably various and yet highly interrelated part of that world.

In dealing with so broad and rambling a subject as the science and technology involved in communication satellites, some sort of organization is necessary. Since I do not know how else to proceed, I propose to be guided by chronology, and discuss matters in the order in which they became clearly apparent to those connected with the Echo and Telstar programmes.

Certainly, none of the technical problems would have arisen had there been no over-all communication satellite programme. For this we must give due credit to Arthur C. Clarke, who in 1945 proposed the relaying and broadcasting of electromagnetic communication signals by means of manned "stationary" satellites at an altitude of 22,300 miles. Yet we see that there was a considerable gap between satellite communication as Clarke proposed it and as it has been realized, for while many of you have seen television relayed across the ocean by Telstar, the manned space stations which Clarke proposed still lie in the future.

I am sure that echoes of Clarke's words of 1945 had reached my ears (though I had not read the words themselves) when I first thought seriously about satellite communication in 1954. It seemed clear to me then, as it does now, that the best justification for communication satellites would be to link together the common-carrier communication systems of various continents. This would, as an example (I use today's figures), make the 46 million telephones of Europe more readily and more quickly accessible to the 83 million telephones of North America.

Broadcasting directly to home receivers would necessitate putting heavy, high power, complicated equipment in a satellite, but my calculations showed that very low power equipment aboard a satellite could provide for the present rapid growth of international telephone and data transmission, and for the first time link together the television networks of various continents.

In 1954 I was worried about problems of the life and reliability of any equipment launched in orbit, and I was encouraged to find that it would be possible to relay telephone and television signals via a passive, spherical, reflecting satellite. Indeed, some of my calculations assumed a 100-foot diameter reflecting sphere, and that is the very diameter of the Echo I balloon satellite which was launched into orbit on 1960 August 12.

Thus, Clarke proposed one thing in 1945; I had something rather different in mind in 1954, which I published in 1955. Something very close to the satellite I described was launched in 1960. Was this a direct result of my 1955 paper ?

Oddly enough, the Echo balloon satellite itself came from work of a quite different character and purpose. In 1956 January William J. O'Sullivan of the Langley Research Laboratory of the National Advisory Committee for Aeronautics, now incorporated in the National Aeronautics and Space Administration, proposed to launch balloon satellites in order to measure the density of the very tenuous atmosphere at an altitude of around 1000 miles. His work led to the construction of an experimental 100-foot aluminized balloon.

After the launching of Sputnik late in 1957 and Explorer I early in 1958, Rudolph Kompfner and I became very concerned about a practical communication satellite experiment. We saw in O'Sullivan's balloon the very object I had thought of in 1954 as a communication satellite. Our discussions with N.A.S.A. led to their Echo programme by early 1959. N.A.S.A. would launch a 100-foot balloon satellite, for measurement of atmospheric density and for communication. The Bell Telephone Laboratories would construct an east coast communication terminal at Crawford Hill in New Jersey, and the Jet Propulsion Laboratory of N.A.S.A. would construct a communication terminal at Goldstone, California. All this was done, and President Eisenhower's spoken message was sent from coast to coast via Echo on 1960 August 12.

Let us note briefly that the density of the atmosphere was duly derived from the orbital behaviour of Echo I. R. W. Bryant, one of those concerned with this work, observes:

> "It must be pointed out in considering these density values that the atmosphere cannot be considered static at high altitudes. The diurnal effect can produce changes in density of as much as a factor of 30, and the effects associated with solar activity can produce changes of as much as a factor of 4 and possibly much greater. The seasonal effect may be as much as a factor of 1·5."

Let us return, however, to Echo I as a communication experiment. One important problem in carrying out such an experiment was that of pointing the transmitting and receiving antennae at the satellite. This could easily be done visually at night during clear weather when the satellite was in sunlight, but these qualifications are severe limitations. The satellite could be tracked by radar. But, Newton's laws of motion and gravitation, which enabled Halley to predict the return in 1757 of the comet of 1682, which now bears his name, would make it possible to predict from data acquired at one time, exactly where the antennae used in the communication experiment should be pointed at another time. Moreover, by using modern electronic gear, the antennae could be made to track the satellite automatically on the basis of the predicted position.

In Project Echo, the existing Minitrack network was the chief source of orbital information as long as the 108 Mc/s beacon on the satellite remained active. Optical data from the Smithsonian Astrophysical Observatory were also used. Radar data from the west coast communication terminal of the Jet Propulsion Laboratory, at Goldstone in California, were available during 1960.

In tracking Echo, orbital elements were computed at N.A.S.A.'s Goddard Space Flight Center at Greenbelt, Maryland. From these, elevation and rate of change of elevation, and azimuth and rate of change of azimuth were computed for times four seconds apart for each pass. To each such set of four data the time was added, and all the data for a pass were punched on a standard teletypewriter tape. Such tapes were transmitted to Holmdel, Goldstone and other locations by commercial teletypewriter circuits. At Holmdel, the received tape was put into a digital-to-analogue converter. When the clock time coincided with the time written on the tape, the angles and rates of change of angles were automatically read out, converted to analogue form, and used to drive the transmitting and receiving antennae.

In the Echo experiment, this pointing was accurate to $\pm 0°{\cdot}2$ under favourable conditions. Such accuracy was not sufficient for Telstar, because the beam width of the Andover antenna is only $0°{\cdot}2$. At the Telstar ground terminal at Andover, Maine, a precision tracking antenna, operating on a 4000 Mc/s signal radiated by the satellite, supplies data from which orbital elements are computed. It was predicted, and this has been borne out in practice, that data from no more than two successive passes per day would make possible a prediction of pointing angles with an accuracy of $0°{\cdot}02$ for the subsequent 24 hours.

Programs for computing orbital elements and tracking data have been written for both the IBM 7090 computers at the Bell Laboratories' Murray Hill and Whippany locations, and for the two IBM 1620 computers located

at Andover. The 7090 makes an orbital determination in a few minutes; the 1620s require about an hour and a half to process the data recorded during a pass, but are adequate to handle three satellites in orbit.

We have seen how O'Sullivan's interest in the density of the exosphere was an important factor in leading to satellite communication. We see that the existence of electronic digital computers was essential in bridging the gap between Newton's laws and the position of Echo I and Telstar I, so that orbital computations could be made in minutes instead of months. As a communication engineer I do, however, propose to say something about electrical communication during this lecture.

One of the great challenges of the Echo experiment was that the 100-foot balloon reflected into the receiving antenna only about 10^{-18} of the 10 kilowatts beamed at it by the transmitting antenna. The very small signal power received had to compete with noise from various sources. When I first considered satellite communication in 1954, by far the greatest source of such noise was the microwave receiver itself. I assumed that the receiver would introduce a noise equivalent to the Johnson or thermal noise of a body at a temperature of about 900 °K.

Happily, by the time that the Echo experiment was carried out, matters had changed drastically. As a result of his studies in microwave spectroscopy following World War II, Townes invented the ammonia maser in 1954. This was followed by the invention of the three-level solid-state maser by Bloembergen, and, by the time that Project Echo was carried out, it was possible to use as an amplifier a maser which introduced a noise corresponding to the electromagnetic radiation from a body at a temperature of 8 °K, an improvement by a factor of 100 over the receiver I assumed in 1954.

What would be the advantage of using such a receiver? This would depend on how much noise reached the receiver from the antenna. In 1954 this would have been negligible in comparison with the 900° noise temperature of a microwave receiver; in the Echo experiment it could be crucial in comparison with the 8° maser noise temperature.

The first requirement was that the antenna should look, not at the warm Earth, but at the cool sky. Antennae using conventional dish-shaped parabolic reflectors see something of the environment to the sides and behind as well as in the direction in which they are pointed. Fortunately, in 1941 Friis and Beck had described a "horn reflector" antenna which is insensitive to radiation from the sides and back.

Even supposing that the antenna saw only the sky, what noise would be received? If the air were perfectly transparent, it would receive only noise from space; but, because air is not perfectly transparent, some thermal radiation must be received from it.

In 1947, Van Vleck gave formulae for the absorption of microwaves by oxygen and water vapour. Using these, together with constants which had been determined experimentally, and data concerning the density and temperature of the atmosphere, D. C. Hogg was able to compute the thermal noise which should be received at various zenith distances as a function of receiver frequency.

It remained to verify this experimentally. By 1959 September this had been done, using a maser with a small horn-reflector antenna. At 6000 Mc/s, theory and experiment agreed within a few per cent. There are, however, other sources of noise. For example, two sources of noise may arise during

rain, namely, thermal noise due to the rain itself, and scattering into the receiving antenna by the rain, of energy from microwave transmitters at a distance.

The maser was instrumental to the success of Echo and later of Telstar. The sensitivity of the maser made an investigation of sky noise imperative. This called into use the horn-reflector antenna, and the results of the investigation confirmed the gains to be made through the use of this type of antenna. Thus, for the Echo experiment a horn-reflector antenna with an aperture of 400 square feet was constructed at Holmdel, and a 3600 square foot antenna was constructed at Andover for the Telstar experiment.

The construction of such large antennae led to the problem of boresighting, that is, of determining just where the antenna beam is pointed for various mechanical positions of the structure. This is no easy problem for a large antenna. The electromagnetic point source which is used must lie outside the Fresnel zone, which means that it must be at a distance of more than D^2/λ, where D is the diameter of the antenna aperture and λ is the wavelength. For an antenna 70 feet in diameter and a wavelength 1/6 foot (a frequency of 6000 Mc/s), this means that the source used in boresighting should be more than 30,000 feet away. Aircraft and helicopters come to mind, but these are expensive and cumbersome.

Happily, radio astronomy has provided us with the locations of a number of sufficiently distant radio sources which are identified with optically observed celestial objects. Some of the stronger sources are Cassiopeia A, Cygnus A, Taurus A, and Virgo A. Each of these sources can provide a number of data points as it moves across the sky. In particular, it is very useful to include at least one whose declination is approximately equal to the observer's latitude, for it will then pass very near to the zenith and thus become a sensitive indicator for azimuth boresighting.

Early in 1962 the antenna at Holmdel was boresighted using radio stars. The tracking equipment was supplied with digital data which would cause it to point exactly at a star and track it if the electrical and mechanical axes of the antenna were exactly aligned. A boresighting correction was obtained through offsetting the antenna in alternate senses by amounts that would reduce the output to a particular chosen value; the true direction of the source was taken as halfway between such offsets in azimuth and elevation. The r.m.s. scatter of the data was 0°·01 in elevation and 0°·025 in azimuth. The beam width at 2390 Mc/s is 1°·4, and so pointing errors could be determined to 1/60 of the beam width or better. The Andover antenna was also boresighted by the same method.

It seems only fair that we should try to repay our debt to radio astronomy. At present, A. A. Penzias is working to set a meaningful upper limit to the abundance in space of the *OH* radical, which has a spectral line at 1677·34 Mc/s. The sensitivity of the Holmdel receiver will allow an improvement of two orders of magnitude over published results.

Navigation, geodesy and chronometry were once near the heart of astronomy, and Telstar I has made its contribution in this field. On 1962 August 25 and 27 William Markowitz and C. A. Lidback of the U.S. Naval Observatory co-operated with J. McA. Steele of the National Physical Laboratory (who suggested the experiment) in relating the master clocks of the Naval Observatory at Washington and the Royal Greenwich Observatory at Herstmonceux to an unprecedented accuracy. This was carried out by

transmitting pulses from the ground stations at Andover and at Goonhilly. The difference in time between the received and transmitted pulses was measured at each station. In addition, Goonhilly measured the arrival of its own pulses as retransmitted by Andover. These data furnished both the clock difference, as represented by the two pulsers, and the travel time. The difference between the Andover and Goonhilly clocks was determined to 1 microsecond. This is an improvement of nearly a thousand to one in accuracy of clock synchronization compared to previous radio transmissions. The clocks at Washington and Herstmonceux were related to Andover and Goonhilly to within about 10 microseconds, but this can be improved to 1 microsecond.

The measurements also gave a check on the accuracy of the orbital data; the ephemeris range was found to be accurate to about 1 kilometre.

I now propose to turn to another topic of considerable interest to science. Prior to the launching of Telstar, our knowledge of the spectrum of electron and proton radiation in the Van Allen belt was meagre, and we had little knowledge of how this radiation changed with time. Fortunately, a long programme concerned with radiation damage to semiconductors, and a small but active interest in low energy nuclear physics had led to semiconductor particle detectors of great simplicity and accuracy. Telstar I was equipped with such detectors. Such detectors have been flown in the Injun and T.R.A.A.C. satellites and in several Air Force satellites in the past two years, but little information is yet available from these experiments.

The detectors are p-n junction devices which in effect are small solid-state ionization chambers. They give output pulses proportional to the energy deposited by an incident charged particle in a disk-shaped active volume a few millimetres in diameter and a few tenths of a millimetre thick. This kind of device has been extensively used in low energy nuclear physics experiments in the last few years, and provides high energy resolution and relatively high speed. In the Telstar experiment the devices were not used as high resolution devices or at their maximum speed; nevertheless, the nuclear physics experience with them was invaluable in the satellite experiment design.

Three detectors measure protons in energy regions, 2·8 to 25 Mev, 26 to 34 Mev, and above 50 Mev. The peak flux of the highest energy protons in the inner Van Allen belt is very similar to the figure given by Van Allen in 1959, and the flux of lower energy protons rises steeply as had been observed at low altitudes by Naugle and Fichtel. Quite comprehensive maps of these particles have been made over the range of Telstar's orbit. Protons are responsible for a major part of the radiation damage on the Telstar solar power plant, and would be much more serious were it not for relatively thick sapphire shielding of the solar cells.

A fourth semiconductor particle detector is studying the distribution of electrons in the trapped radiation belts. In this case, particle pulses are sorted into four pulse-height channels below 1 Mev. Because of the nature of electron energy loss processes, the detector is also sensitive to electrons of higher energy.

Data on magnetically trapped particles are most naturally presented in co-ordinates reflecting the basic properties of the Earth's magnetic field. In a five-day period during July, approximately two weeks after Telstar's launching, measurements of the electron counting rate were obtained through

much of the space bounded by the perigee and apogee, 1·08 and 1·93 earth radii (R_E) from the centre of the Earth respectively, and by geomagnetic latitudes $\pm 58°$, though measurements were lacking at intermediate altitudes in low latitudes, and at high altitudes in high latitudes. These data have been computer sorted, and contours of constant omnidirectional flux derived. Assuming that the electron energy spectrum is appropriate to fission fragment beta decay, the contour corresponding to 10^9 electrons/cm^2 sec is found to extend from 1·21 to 1·82 R_E on the geomagnetic equator, and is believed to reach $\pm 20°$ latitude at 1·4 R_E. The flux falls rapidly toward lower altitudes, and more slowly toward high latitudes and high altitudes, being about 10^5 electrons/cm^2 sec at $\pm 45°$, 1·4 R_E, and on the geomagnetic equator at 1·15 R_E. The intensity at the lowest contour derived was about 300 electrons/cm^2 sec.

Initially, the electron flux measured by Telstar I was about ten times as great as had been expected, and the electron energy was considerably greater than had been expected. This is generally attributed to the high-altitude detonation of a nuclear device in the megaton yield range in the Pacific on the day before Telstar was launched.

The unexpected radiation measured by Telstar, and measured at lower altitudes by the Injun satellite, caused considerable scientific excitement. On October 27, N.A.S.A. launched the Explorer XV radiation measuring satellite. Despite the fact that the de-spin mechanism failed, this satellite has added valuable data to our knowledge of the Van Allen belt and the way that it changes with time.

The radiation measured by Telstar I was unexpectedly high. So was the public excitement engendered by the first and by subsequent real-time transatlantic television programmes which Telstar I made possible. A United States Information Agency poll showed that in the week following the transatlantic television ceremonies of 1962 July 23, 82 per cent of the population of Great Britain were able to identify the Telstar satellite by name, 79 per cent knew it was a U.S. achievement and 59 per cent saw the television programme beamed from the United States. In a message broadcast to the people of the Commonwealth on Christmas Day, 1962, Queen Elizabeth referred to Telstar as "the invisible focus of a million eyes", and used this new star to draw man's attention to the star which the Wise Men of old followed, and to its message.

Telstar was an engineering experiment which took us a step forward in understanding and capability. The interest excited by Telstar made people want to know when satellites would become a regularly functioning part of the world's communication network, what sort of satellites would be used, and how a satellite communication system would be brought into being.

When work was started toward an experimental active communication satellite in the research department of the Bell Telephone Laboratories late in 1959, we had a great enthusiasm for a 24-hour synchronous satellite which would hang stationary above a spot on the equator at an altitude of 22,300 miles. We realized, however, that the time delay in transmission might seriously impair the usefulness of such a satellite for telephony.

While long distance or trunk telephone circuits use separate paths in the two directions, the circuits from switching offices to subscribers send signals both ways over the same pair of wires. Devices called hybrid coils are used

to attain some degree of independence of transmission in the two directions. Nonetheless, all of the world's 140 million telephones reflect several per cent of energy directed toward them. When the talker hears this reflected speech delayed by a tenth of a second or more, it has an intolerably unpleasant and upsetting effect. Thus, "echo suppressors" are inserted at the ends of trunk circuits which are longer than 1500 miles. These devices turn off the outward path when a signal is present on the inward path. Provisions are made for breaking in by talking very loudly.

Echo suppressors are tolerable for delays encountered in continental telephony and even for trans-oceanic telephony via submarine cable. Would they be tolerable for an echo delayed $0^{s}{\cdot}6$, as would be the case in talking via a synchronous satellite ?

This is no easy matter to decide, for the answer could depend on the people involved, on the nature of the conversation and, perhaps, on the design of the echo suppressor. Psychologists have been studying this problem at the Bell Laboratories for over two years. As in the case of most experiments, answering one question leads to another. However, we hope to publish convincing numerical data within a few months. At present, I can only say that under realistic conditions, a delay of $0^{s}{\cdot}6$ in combination with the best echo suppressors available, proves unacceptable in a substantial fraction of conversations.

This result seemingly flies in the face of the fact that laboratory workers often feel, after casual trials, that a circuit using echo suppressors which has a delay of $0^{s}{\cdot}6$ is quite satisfactory. It is here that we see the difference between experimental science as we know it in our time and the sort of casual experience which was man's sole and inadequate guide in earlier ages.

In citing this example of human response to a communication system, I have strayed from physics, but I have not departed from the realm of science and technology. Satellite communication itself has stirred other realms. I think I need scarcely describe the somewhat heady, or perhaps I should say dizzy, feeling I had during a period when the President of the United States and members of Congress proposed and discussed legislation engendered by the existence of a communication satellite, a satellite whose very existence depended in part on earlier work of mine. Perhaps the dizziness was caused by the stupendous gulf, physical and otherwise, which separated me from the political scene; I followed events in the newspapers, but I had no direct part in them.

On 1962 August 31 President Kennedy signed a Communications Satellite Act which, after long hearings and much debate and amendment, had passed both houses of Congress. This act sets the pattern for United States participation in any international civilian satellite communication system. The exclusive right is granted to a new corporation created by law for this single purpose.

Traditionally, the communication common carriers have had freedom to use directly, as a part of their very diverse communication facilities, any part of the science and technology which has come to them from so many sources. Thus, their facilities have come to include wire, cable, coaxial cable, submarine cable, short-wave radio, ultra-high frequency radio, tropospheric scatter and microwave radio relay systems.

The Communications Satellite Act and the entirely new corporation which it has created, represent a bold venture into completely uncharted waters.

Its activities are confined to one particular aspect of common carrier communication-supplying circuits by means of satellites. The stock is to be owned partly by the general public and partly by communication common carriers. The board of directors is to have members representing the non-communication investors, who presumably want to make money, the common carriers, who urgently need more trans-oceanic circuits, whether these be supplied by cables or by satellites, and members appointed by the President, who has strongly asserted that satellite communication should serve the needs of the inhabitants of the least developed areas of the globe. For this new and unique corporation to act successfully in establishing the necessary research and development resources and reaching its various goals surely and promptly in a tricky and scarcely tried field of technology, will be a historic example of American pluck and ingenuity.

I opened by proclaiming myself no historian, and I am certainly no prophet. In closing, let me return to the things that I have observed over the few years of my life that have been devoted in part to communication satellites.

I think that the relationships I have pointed out between work on Echo I and Telstar I and the fields of upper atmosphere physics, celestial mechanics, electronic computers, molecular spectroscopy and masers, radio astronomy and experimental psychology, aptly illustrate the fact that the science and technology involved in any complicated undertaking come from so many sources that no one can call them his own. Science and technology belong to no enterprise and to no nation; they are part of the heritage and the work of men throughout the world. Governments and other institutions may support, licence, forbid, and enforce conformity, but they can neither legislate the laws of nature out of existence nor prevent men outside their control from discovering and using them. But the powers that governments exercise can have drastic effects, both on the lives and work of scientists and engineers and on the benefit that society reaps from science and technology. And, these powers are as often exercised foolishly and ignorantly as they are with informed wisdom.

C. P. Snow has spoken of two worlds in modern society—the world of polite learning and the world of science and technology. I myself find a more real distinction between two other worlds. These two worlds can exist even in the thought and action of one individual, though perhaps they more often manifest themselves separately in, say, an engineer as contrasted with a statesman or a religious leader.

One of these worlds has two aspects; natural law, and the understanding and application of natural law which are expressed in our science and technology. Some things are possible; some are beyond possibility. At a given time, we can in part distinguish between the possible and the impossible. Of those things which are possible, some we can this very day achieve by an effort commensurate with their value. Some we can have, but at far too dear a price. Some, though possible in principle, are beyond our present grasp, however hard we may strive. This world of our understanding of nature and the power that it gives us, varies not only with time, but among individuals and institutions. What one can do is beyond the grasp of another. Yet, whatever ephemeral and elusive equalities this world of science and technology may appear to have, it is exceedingly powerful, though extremely obdurate.

The possibilities of great things are within our grasp, and men and institutions exist by means of which these great things can be accomplished.

The other world is, let us say, a personal world, the world of our aspirations—of our needs, desires, dislikes and hates. It is the world of what we would like to accomplish and of how we would prefer to achieve it. The obdurate world of science and technology can sometimes help us to distinguish wishful thinking from what is possible, of fantasy from what will work. It can sometimes enable us to foretell otherwise unexpected and unpleasant consequences of capricious behaviour.

Projects and people succeed in the degree that their aspirations are wise and realistic. I believe that our knowledge of the powerful but obdurate world of science and technology can add wisdom and realism to our world of personal and national conduct. But I believe also that too often men and nations expect the laws of nature, the state of technology, and the abilities of people and of institutions, to conform to their aspirations, rather than make their aspirations conform to the obdurate world of science and technology.